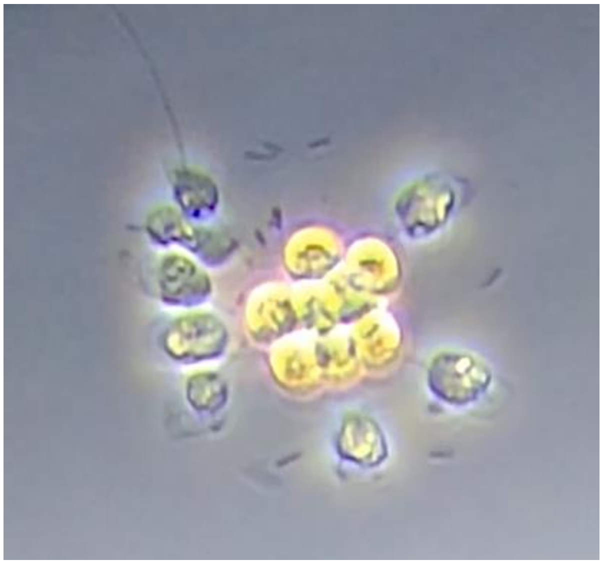
A child-centric microbiology education framework

Microbial Food Webs

Granny: spiders' webs catch flies to eat; do microbial food webs catch microbial food?



William D. Orsi

Department of Earth and Environmental Sciences, Paleontology & Geobiology, and GeoBio-CenterLMU, Ludwig-Maximilians-Universität München, Richard-Wagner-Strasse 10, 80333 Munich, Germany.

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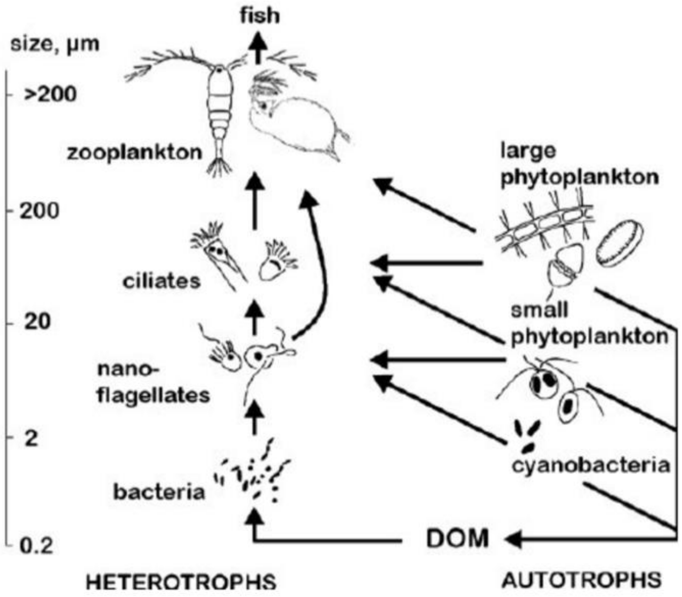
Storyline

Whoever has gone swimming in a lake or the ocean has perhaps unknowingly experienced and interacted with a microscopic and vast unseen biosphere of aquatic microbes. A single milliliter of seawater has over one million microbial cells, which can only be observed with a microscope. In fact, there are so many microbial cells in the ocean, that if you were to line them up end to end, the entire length would encircle the milky way galaxy! Although unseen to the naked eye, the microbes living in aquatic ecosystems form complex food webs that support the growth of animals such as fish, and the activities of these food webs helps to keep the ecosystems healthy. In principle, it is not difficult to observe these microscopic ecosystems – all that is needed is a light microscope. The photo above, taken with an iPhone camera through the eye piece of a light microscope, shows a microbial food web observed from a lake in Bavaria (Germany), which exemplifies some key features of microbial food webs. The size of the cells in the image is magnified 1000 times, and thus the actual size of these microbes is roughly 1000 times smaller than they appear in the photo, so they are invisible to the naked eye. The cluster of yellow cells in the middle represent a colony of photosynthetic algae that use sunlight to produce sugars. The small black elongated rods are bacteria that are attracted to the area by the high concentration of sugars, and swim around the colony accessing the new food. The larger green cells forming a ring around the perimeter are microscopic predators: single celled flagellated protozoa (microbial eukaryotes), that swarm around the colony and feast upon the bacteria (see accompanying video). Anyone equipped with a smart phone and a basic light microscope (or Foldscope) can look at aquatic microbes in this manner which can be a fascinating journey into the world of microbes both for children and teachers.

The Microbiology and Societal Context

The photograph displayed above serves as an analogy for the larger importance of microbial food webs. Interactions such as these can be considered a sort of 'microbial feeding frenzy', and are analogous to feeding frenzies of fish, birds, and other marine wildlife that are observable without a microscope. The microbial feeding frenzies shown in the photo are directly responsible for controlling how much food is available to the higher trophic levels (the position occupied in a food web), like fish. And, this ultimately controls how much food is available to the predators of fish such as birds, and also us humans. All of the food that is created in aquatic ecosystems, and terrestrial ecosystems for that matter, is ultimately derived from sunlight. Sunlight fuels the photosynthesis, that allows the algae to grow, which provides food for the bacteria, that then serve as food for the micro-zooplankton and zooplankton – the small and large floating animals. This energy is then transferred up the food chain and ultimately sustains human civilization. For those of us with a vegan or vegetarian diet, and eat only plant-based foods, the role of photosynthesis in sustaining our lives is quite clear. But, even if meat is consumed (either fish or land animals), the ultimate source of energy is always the sun. Thus, the energy stored in the chemical bonds that make up nearly all life forms, including us humans, is all derived from the energy in sunlight as the original source of energy. Microbial food webs such as those depicted in the introductory photograph play an integral part in controlling the upward flow of energy in this larger food web, from which many of us (and other animals) derive our food (Box 1).

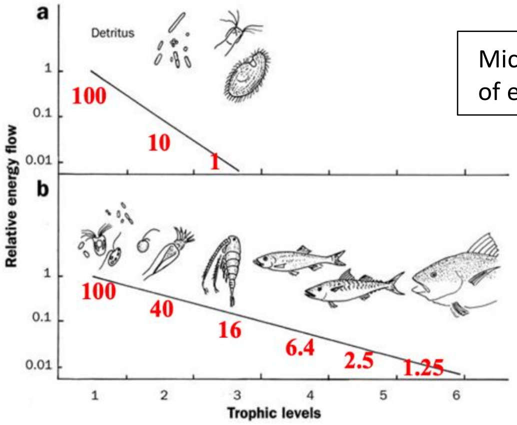
Box 1: Microbiology themes treated in this chapter. Diagram is derived from 'Marine Ecological Processes' (Tom Fenchel, 1987, *Limnology and Oceanography*).



Microbial Food Webs: the Microbiology

1. ***The microbial food web determines the amount of food that is produced in a food chain.*** The length limit of a food chain is reached when about 1 percent of the original energy input remains. Because aerobic metabolism (a metabolism that consumed oxygen) produces more energy compared to an anaerobic metabolism (a metabolism without oxygen), a longer food chain can be supported in ecosystems where oxygen is present (Box 2). Since microbial food webs are the base of the larger food chain, the amount of energy that is transferred between microbes at the beginning, determines how many other trophic levels can be supported later on. This is displayed in Box 2. The food chain without oxygen is shorter compared to the food chain where oxygen is present (the red numbers indicate how many units of energy are transferred to the next level from the preceding level). Because anaerobic metabolism in the anoxic microbial food web is only able to transfer ca. 10% of energy to the next level, the end of the food chain is reached very early, and no larger animal life can be supported in later parts of the chain. In some anaerobic, dark biospheres, the food webs are very limited due to restricted chemical energy, and thus often only contain bacteria, archaea, and viruses. However, when oxygen is present, ca. 40% of energy can be transferred to the next level in the microbial food web, and in this case larger animals can be supported in the food chain all the way up to the great blue whale.

Box 2: The effect of oxygen on microbial food webs, and the larger food web involving animals from Tom Fenchel and Bland Finlay, 1995).



Microbial food web without oxygen: only 10% of energy can be transferred to next level.

Microbial food web **WITH** oxygen: **40%** of energy is transferred to next level, which supports a food chain with animal life.

2. *Microbial food webs control the amount of oxygen in the ecosystem.* Photosynthetic activity of algae, and their production of new food, is limited by inorganic (non-carbon) nutrients (nitrogen and phosphorous), and so the more nutrients available, the more active the microbial food web. Looking at Box 2, we might think that if more nutrients are available, more photosynthesis will produce more oxygen and make the ecosystem more productive. However, this is restricted to only a few regions of the ocean where there is a lot of physical mixing of the water which helps to continually flush the ecosystem with oxygen. In most cases, where there is less physical mixing of the water (like a lake or pond), increased nutrients ultimately lead to oxygen depleted conditions and the reduction of animal life. That is because, the bacteria feeding off of the increased amount of food produced from photosynthesis (resulting from the excess nutrients) also consume oxygen. Eventually if nutrients are not reduced, and oxygen is not re-introduced from mixing, the microbial life will consume oxygen down to levels that no longer can sustain a larger food web including fish and larger animals. This is why it is so important to monitor the input of nutrients like nitrogen and phosphorous into aquatic ecosystems that are close to agricultural areas where fertilizers are often applied in high concentrations. An indirect result of too much fertilizer applied to soils can be the destruction of nearby aquatic ecosystems.

The issue of growth limiting factors mentioned here is an important concept in nature: *process- or rate-limiting parameters*, which in this case are initially low nitrogen and phosphorus levels. Where these are available in higher concentrations, they are no longer limiting, and growth accelerates until a new factor becomes limiting, in this case oxygen. We experience process-limiting parameters in all aspects of our lives. Eating is a simple example: when we eat a pizza, we may eat it all. Since we only have one, the amount of pizza is limiting. But imagine we are given 10 pizzas: we might manage 2 but then we become awfully full and start to feel sick. Our stomachs are the new process-limiting parameter.

3. *Microbial webs control the size and abundance of fish and other aquatic animals.* As displayed in Box 2, the microbial food web and interactions displayed in the introductory photograph ultimately control how much fish are present and how large the fish are. Because the fish are dependent on the microscopic life forms as a food source (e.g., algae), the amount of microbial biomass available will determine how much fish biomass can exist. However, as pointed in the previous section, there is a delicate balance between the amount of microbial biomass and the concentration of oxygen. If nutrients increase to levels that cause microbes to grow up to certain levels, the oxygen can be completely removed from the ecosystem resulting in an oxygen-free 'dead zone'. One example of this is the water in the Gulf of Mexico at the mouth of the Mississippi River. High concentrations of nitrogen and phosphorous from over-fertilized soils are brought by the river to the ocean, and the end result is an oxygen free dead zone that is devoid of animal life (Box 3). In contrast, there are other regions of the ocean that have naturally high nutrient concentrations with abundant animal life. There are called upwelling regions, and are found on the west coast of Africa and South America, and are some of the most productive fishing areas of the world. Here, nutrient rich water from the deep sea is brought to the surface supporting photosynthesis, but the water is well mixed and thus oxygen is continually re-supplied. Thus, because oxygen is constantly re-supplied, these naturally productive ecosystems can have both high nutrients, and oxygenated conditions that support a microbial food web with high productivity of biomass, that can then also support an animal food chain. The process limiting parameter in these upwelling regions is often the availability of iron, which can be brought into the ocean from desert dust blown over the ocean from the continents. Iron is required by the bacteria in the ocean that 'fix' N_2 gas out of the atmosphere and bring it into a useable form of other life forms. Thus, while it may seem strange, much of the life in these productive, oxygenated regions of the oceans with animal food chains is often limited by the availability iron which comes via dust storms from the desert.

Box 3: Satellite image of the mouth of the Mississippi River in the Gulf of Mexico. The green color in the water is from blooming algae whose growth is stimulated by the high amount of nitrogen and phosphorous that is brought to the ocean from the river (source: NASA).

4. ***Greenhouse gas emissions can be controlled by microbial food webs.*** Climate change is one of the most important issues of our time, and is caused by emissions of greenhouse gases. Three of the most important greenhouse gases are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which are released as the end products of metabolism from bacteria and archaea that live in soils, sediments, and aquatic ecosystems. The amount of these gases that are released from

ecosystems are determined in large part by the functioning of the microbial food web, because the microbial predators of the bacteria and the archaea (the protozoa) control how many of these greenhouse gas producing cells are present in the environment.

Pupil participation

1. ***Exercises***
    a. Collect water from a nearby ecosystem, this could be a pond, stream or a beach.
    b. Place a drop of water onto a microscope slide, and observe it at ca. 100x magnification using a light microscope.
    c. Collect photographs and videos of the microbes observed, simply by holding the iPhone camera (or any other smartphone camera) against the eye piece and taking a picture or video of cells as they are observed. An example of how such a photo can look is provided on the first page of this chapter.
    d. Identify the observed microbes using an identification guide (for example the book 'Das Leben im Wassertropfen').

2. ***Class experiments***
    a. Add different sources of nitrogen and phosphorous into separate bottles of water collected from a nearby source (lake, stream, or pond).
    b. Add water to a separate flask that does not receive any nutrients.
    c. Observe the development of the microbial food web over time by observing with a light microscope as described above.
    d. Keep a record of the abundance of different groups of microbes based on an identification guide.
    e. Assess the effects of the added nutrients on the abundance and diversity of microbes within the microbial food web, compared the flask that did not receive extra nutrients, after monitoring over a five day period.
    f. What are the end results? How does the increased nutrients affect the microbial food web?

The Evidence Base, Further Reading and Teaching Aids

1. Jed Fuhrman (2011) Oceans of Crenarchaeota: a Personal History Describing This Paradigm Shift. *Microbe* 6(12): 531-537.
2. Tom Fenchel and Bland Finlay (1995) Ecology and Evolution in Anoxic Worlds. Oxford Series in Ecology and Evolution ISBN: 019-854838-9.
3. Tom Fenchel (1987) Marine Ecological Processes. *Limnology and Oceanography* 32(3) 778-778.
4. Dieter Krauter and Heinz Streble (2011) Das Leben im Wassertropfen. ISBN-13: 978-3440126349.
5. Carolyn Kormann (2015) Through the looking glass: can a cheap, portable microscope revolutionize global health? *The New Yorker, Annals of Science* December 21 & 28 issue.